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Gamma Ray Counting for Low Background Experiments

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SNOLAB

Interspec Gamma Ray Software

- https://github.com/sandialabs/InterSpec/releases/tag/v1.0.9

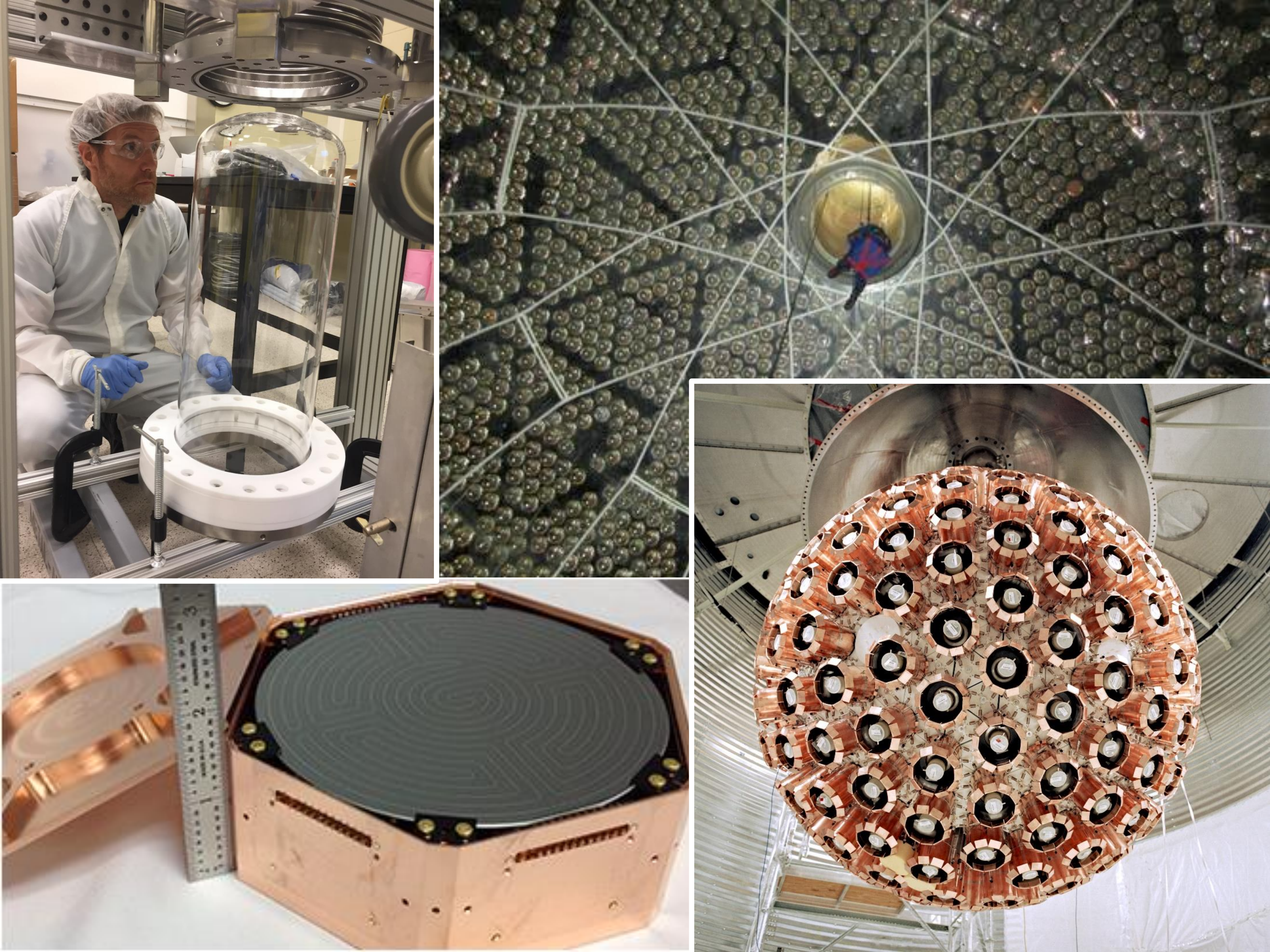
- Please download and install the appropriate version for your OS.

Alternatives To InterSpec

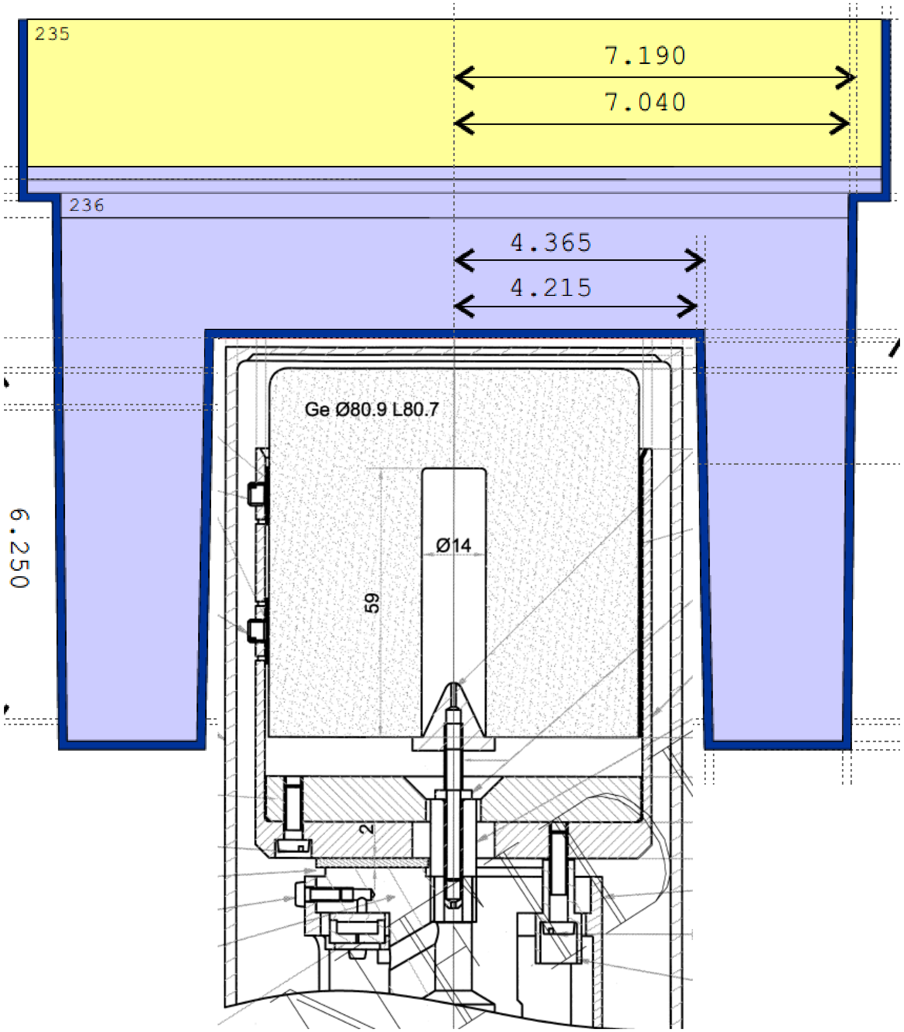
- https://hekili.ca.sandia.gov/CAMBIO/
  - The information will be in different locations

- Work with a friend (maybe on discord)

- Excel, Python, or Google Sheets
  - Open the Mine_Dust_Data_Excel.csv file
  - Use the "integration method" shown at the end of the presentation



Gamma Ray Detection



- High-purity germanium crystal detectors
- Cooled with liquid nitrogen
- Shielded with low-activity copper and lead

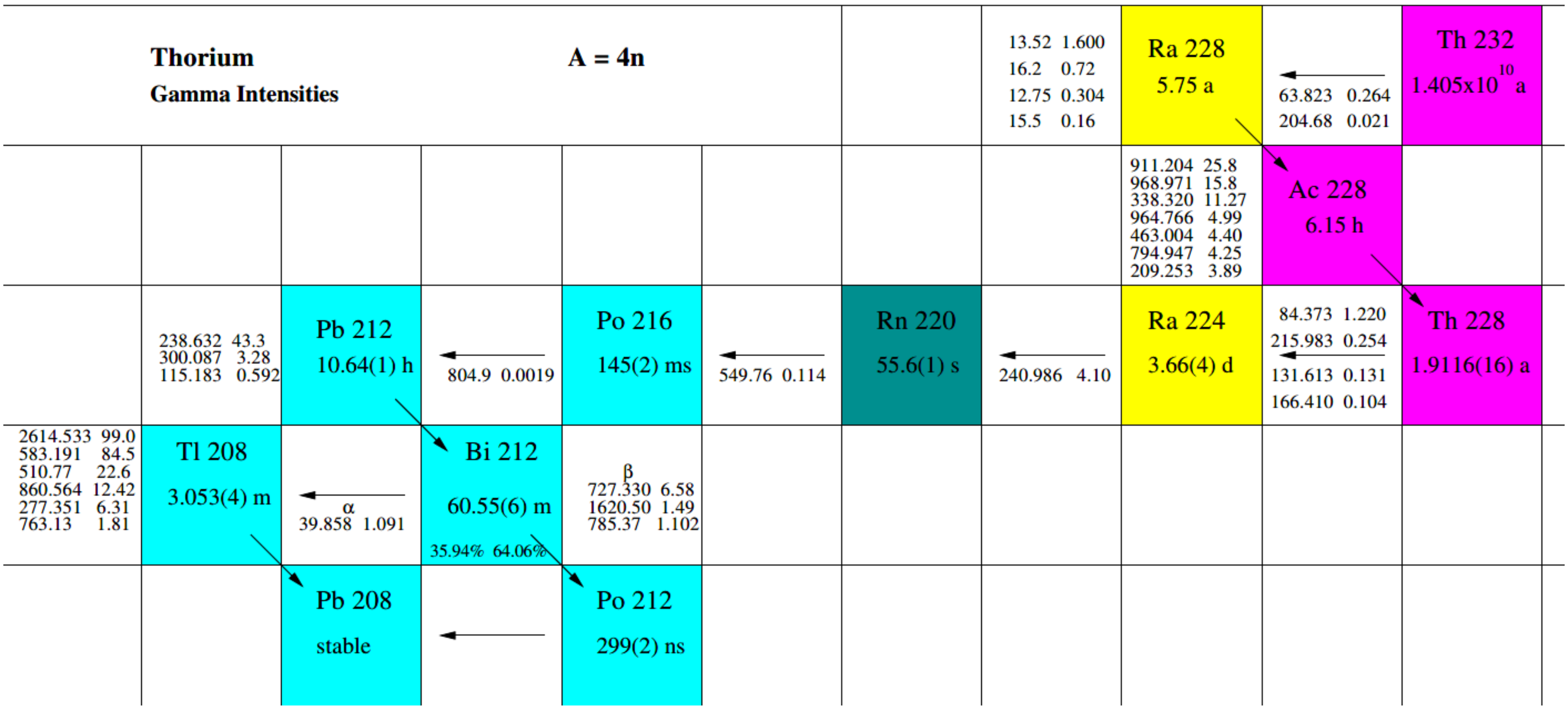
Example Radioactivity Levels

- ^{14}C – 1 ppt of natural Carbon
- ^{40}K – 120 ppm of natural Potassium
- ^{238}U – 1 to 10 ppm in rocks and soil
- ^{232}Th – 1 to 10 ppm in rocks and soil
- Thoriated welding rods: 1-4% ^{232}Th
- Screened low-background materials <1 ppb U, Th
- Rn gas
  - 1 to 100 Bq/m^3 on surface.
  - ~3 Bq/m^3 in Sudbury
  - ~130 Bq/m^3 at SNOLAB

Sources of Radioactive Backgrounds

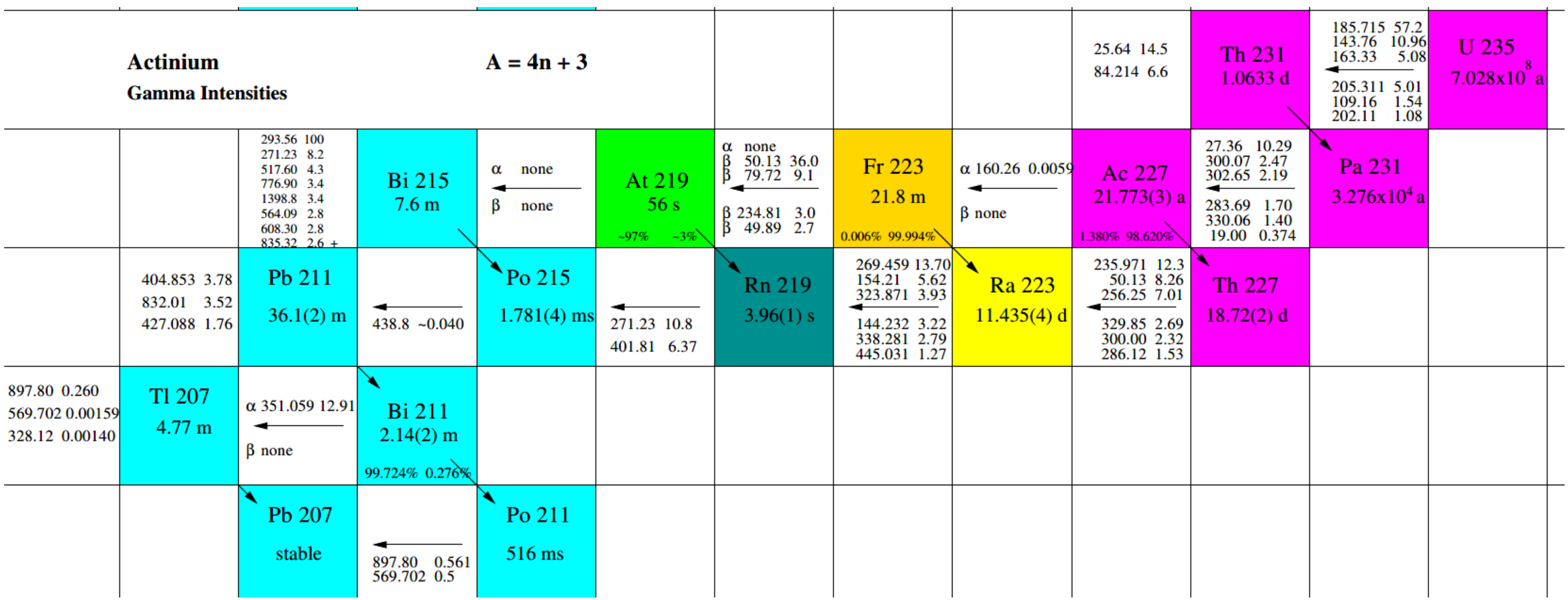
- Nearly stable isotopes
  - ^{238}U – 4.5 x 10^9 years
  - ^{232}Th – 1.4 x 10^{10} years
  - ^{235}U – 7 x 10^8 years
  - ^{40}K – 1.3 x 10^9 years
- Activated isotopes
  - ^{14}C – 5,700 years
  - ^{39}Ar – 270 years
  - ^{7}Be – 53 days
- Daughter isotopes
  - ^{210}Pb – 22 years
  - ^{208}Tl – 3 minutes
  - ^{228}Ac – 6.2 hours
- Gaseous daughter isotopes
  - ^{220}Rn – 56 seconds
  - ^{222}Rn – 3.8 days
  - ^{4}He – stable
- Fission products
  - ^{137}Cs – 30 years
  - ^{131}I – 8 days
- Man-made isotopes
  - ^{60}Co – 5.3 years
  - ^{3}H – 12 years
  - ^{18}F – 110 minutes

^{232}Th Chain



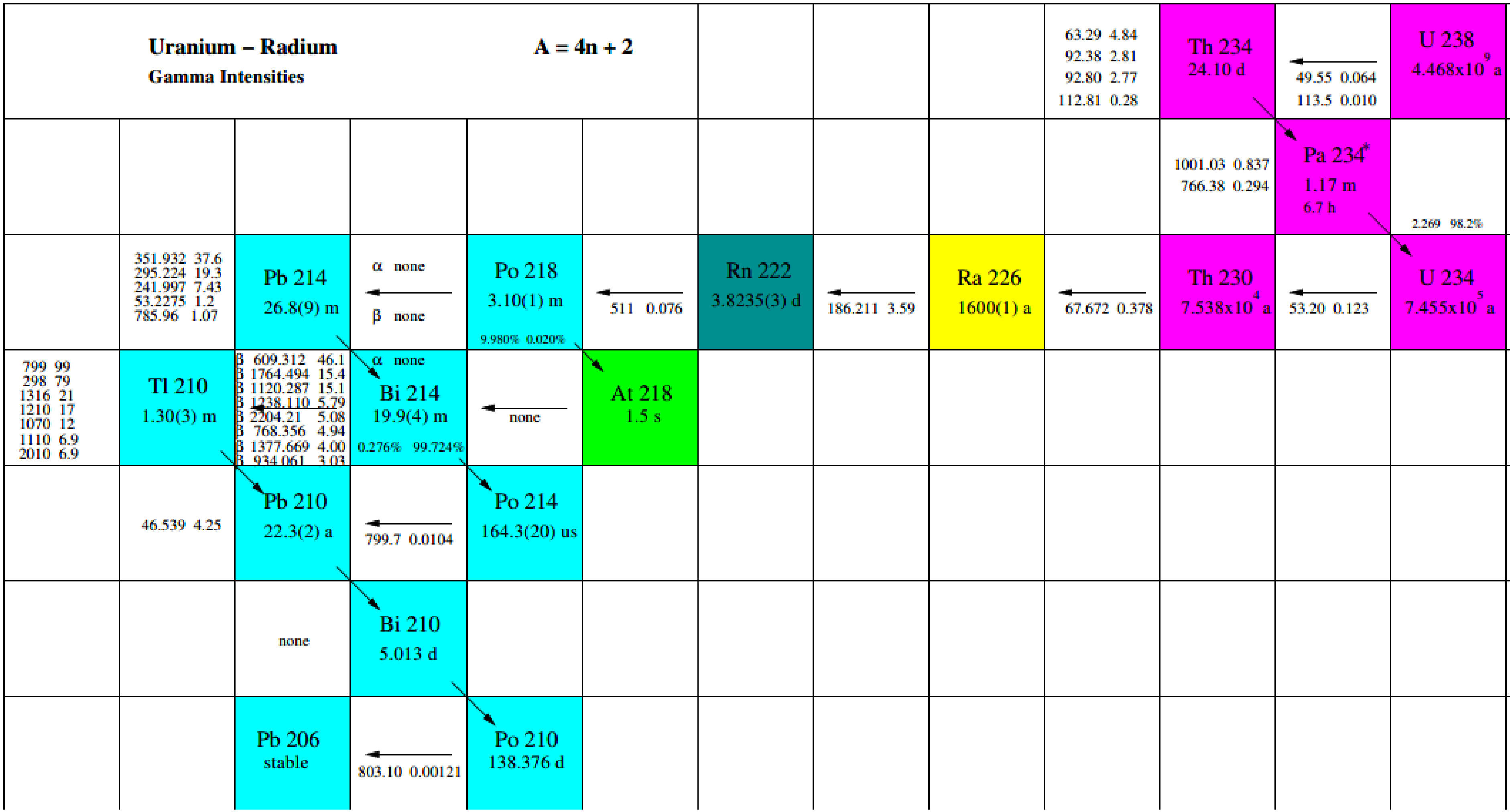
Thorium
Gamma Intensities
A = 4n
Th 232
1.405x10^10 a
63.823 0.264
204.68 0.021
Ra 228
5.75 a
13.52 1.600
16.2 0.72
12.75 0.304
15.5 0.16
Ac 228
6.15 h
911.204 25.8
968.971 15.8
338.320 11.27
964.766 4.99
463.004 4.40
794.947 4.25
209.253 3.89
Th 228
1.9116(16) a
84.373 1.220
215.983 0.254
131.613 0.131
166.410 0.104
Ra 224
3.66(4) d
240.986 4.10
Rn 220
55.6(1) s
549.76 0.114
Po 216
145(2) ms
804.9 0.0019
Pb 212
10.64(1) h
238.632 43.3
300.087 3.28
115.183 0.592
Bi 212
60.55(6) m
35.94% 64.06%
β
727.330 6.58
1620.50 1.49
785.37 1.102
α
39.858 1.091
Tl 208
3.053(4) m
2614.533 99.0
583.191 84.5
510.77 22.6
860.564 12.42
277.351 6.31
763.13 1.81
Po 212
299(2) ns
Pb 208
stable

^{235}U Chain



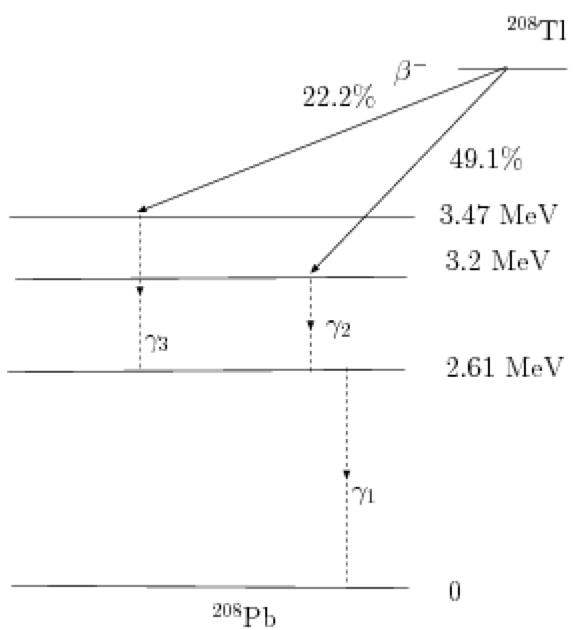
Actinium
Gamma Intensities
A = 4n + 3
25.64 14.5
84.214 6.6
Th 231
1.0633 d
185.715 57.2
143.76 10.96
163.33 5.08
205.311 5.01
109.16 1.54
202.11 1.08
U 235
7.028x10^8 a
293.56 100
271.23 8.2
517.60 4.3
776.90 3.4
1398.8 3.4
564.09 2.8
608.30 2.8
835.32 2.6 +
Bi 215
7.6 m
α none
β none
At 219
56 s
~97% ~3%
α none
β 50.13 36.0
β 79.72 9.1
β 234.81 3.0
β 49.89 2.7
Fr 223
21.8 m
0.006% 99.994%
α 160.26 0.0059
β none
Ac 227
21.773(3) a
1.380% 98.620%
27.36 10.29
300.07 2.47
302.65 2.19
283.69 1.70
330.06 1.40
19.00 0.374
Pa 231
3.276x10^4 a
404.853 3.78
832.01 3.52
427.088 1.76
Pb 211
36.1(2) m
438.8 ~0.040
Po 215
1.781(4) ms
271.23 10.8
401.81 6.37
Rn 219
3.96(1) s
269.459 13.70
154.21 5.62
323.871 3.93
144.232 3.22
338.281 2.79
445.031 1.27
Ra 223
11.435(4) d
235.971 12.3
50.13 8.26
256.25 7.01
329.85 2.69
300.00 2.32
286.12 1.53
Th 227
18.72(2) d
897.80 0.260
569.702 0.00159
328.12 0.00140
Tl 207
4.77 m
α 351.059 12.91
β none
Bi 211
2.14(2) m
99.724% 0.276%
Pb 207
stable
897.80 0.561
569.702 0.5
Po 211
516 ms

^{238}U Chain



Uranium – Radium
Gamma Intensities
A = 4n + 2
63.29 4.84
92.38 2.81
92.80 2.77
112.81 0.28
Th 234
24.10 d
49.55 0.064
113.5 0.010
U 238
4.468x10^9 a
1001.03 0.837
766.38 0.294
Pa 234*
1.17 m
6.7 h
2.269 98.2%
351.932 37.6
295.224 19.3
241.997 7.43
53.2275 1.2
785.96 1.07
Pb 214
26.8(9) m
α none
β none
Po 218
3.10(1) m
9.980% 0.020%
511 0.076
Rn 222
3.8235(3) d
186.211 3.59
Ra 226
1600(1) a
67.672 0.378
Th 230
7.538x10^4 a
53.20 0.123
U 234
7.455x10^5 a
799 99
298 79
1316 21
1210 17
1070 12
1110 6.9
2010 6.9
Tl 210
1.30(3) m
β 609.312 46.1
β 1764.494 15.4
β 1120.287 15.1
β 1238.110 5.79
β 2204.21 5.08
β 768.356 4.94
β 1377.669 4.00
β 934.061 3.03
α none
Bi 214
19.9(4) m
0.276% 99.724%
none
At 218
1.5 s
46.539 4.25
Pb 210
22.3(2) a
799.7 0.0104
Po 214
164.3(20) us
none
Bi 210
5.013 d
Pb 206
stable
803.10 0.00121
Po 210
138.376 d

Gamma Ray Generation

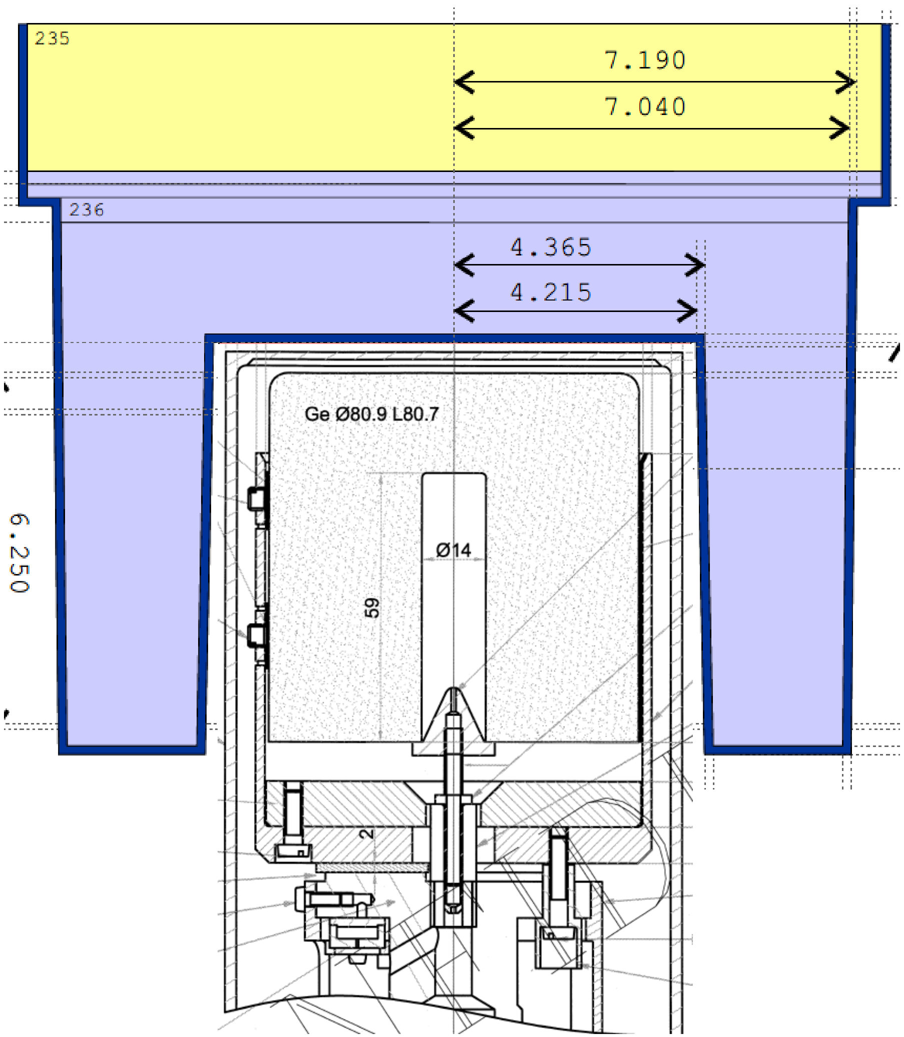


Gammas from ^{208}Tl (3.053 m *4*)

Eg (keV)	Ig (%)	Decay mode
211.40 *15*	0.178 *20*	b^-
233.36 *15*	0.307 *20*	b^-
252.61 *10*	0.69 *4*	b^-
277.351 *10*	6.31 *9*	b^-
277.72		b^-
485.95 *15*	0.050 *5*	b^-
510.77 *10*	22.6 *3*	b^-
583.191 *2*	84.5 *7*	b^-
1381.1 *5*	0.007 *3*	b^-
1647.5 *7*	0.0020 *10*	b^-
1744.0 *7*	0.0020 *10*	b^-
2614.533 *13*	99	b^-

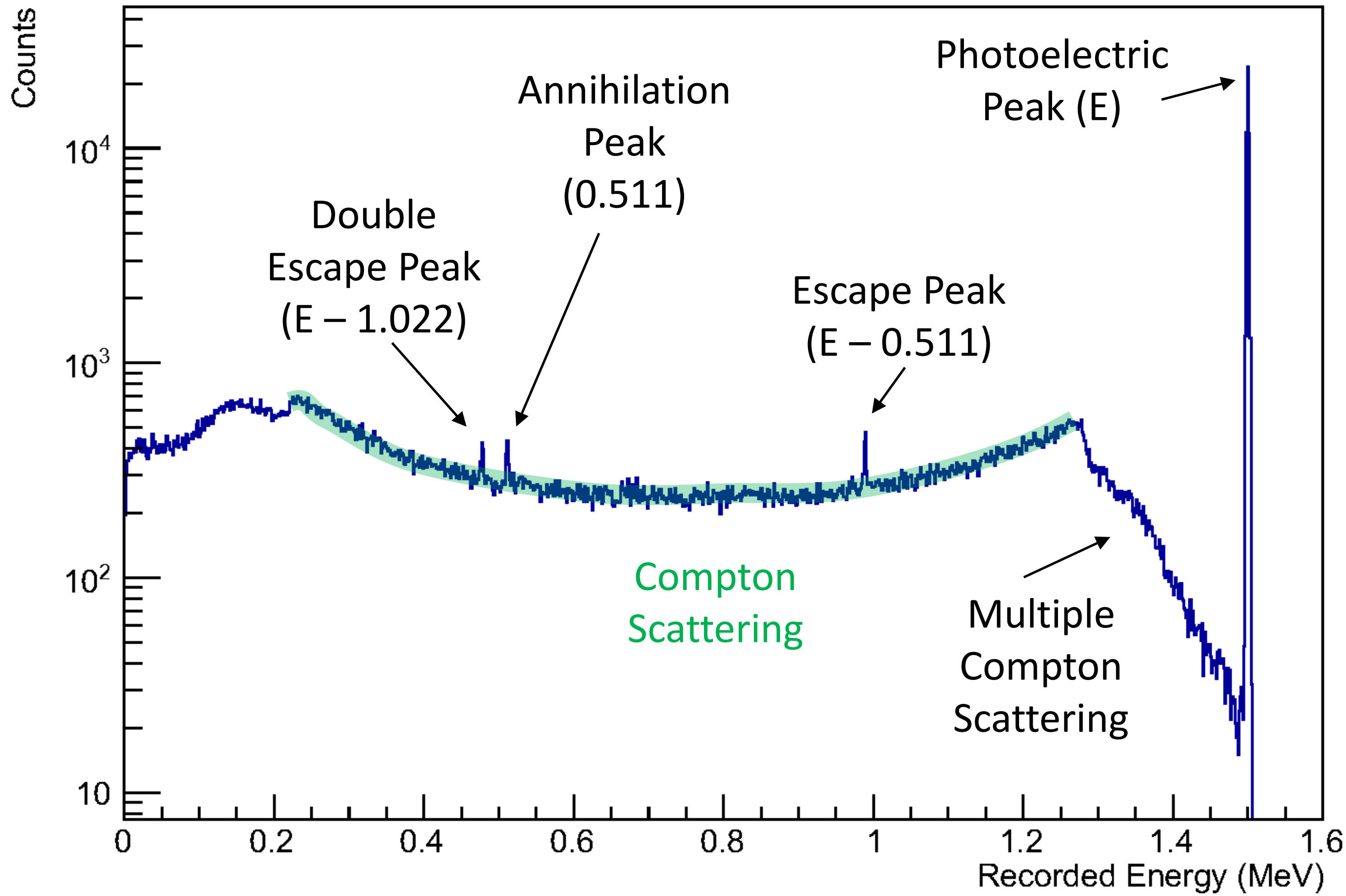
Lund/LBNL Nuclear Data
http://nucleardata.nuclear.lu.se

Gamma Ray Detection



- High-purity germanium crystal detectors
- Cooled with liquid nitrogen
- Shielded with low-activity copper and lead

Simulation of 1.5 MeV Gamma Rays



Line widths are usually set by the resolution of the detector.
Germanium detectors have resolutions of 1 to 3 keV.

Analysis Method

- Focus only on photoelectric peak
- Calculate number of observed events in peak
- Convert to activity for that isotope

$$N = \Omega \, \epsilon \, \frac{Ig}{100} \, M \, t \, A$$

Ω = Solid Angle factor (from Simulations)

ϵ = Photoelectric peak efficiency (from Simulations)

Ig = Branch Probability (from Lund database)

M = Sample mass

t = Data acquisition time

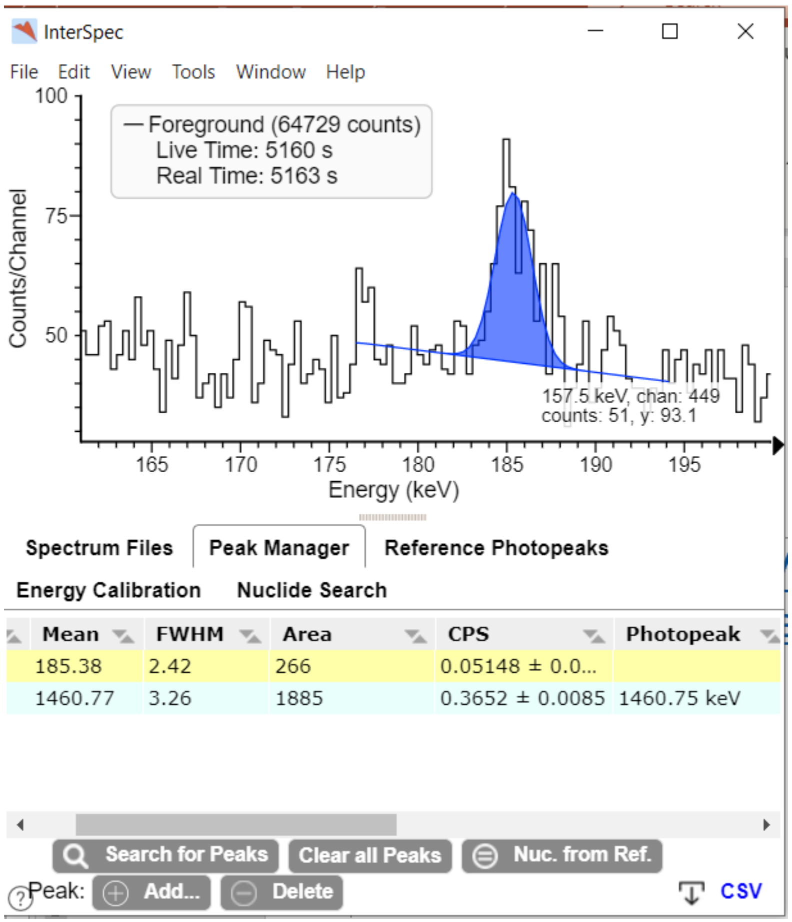
A = Activity (units such as Bq/kg)

Analysis Goals

- What radioactive elements are present in your samples?
- What is the activity (with uncertainty) of each of these elements?
- Are these activities consistent with other measurements?
- Are there any decay chains present?
- Are the elements in the chains in equilibrium?
  - Or have certain elements been concentrated or diluted?
- What are the dominant uncertainties in your analysis?

InterSpec

- https://github.com/sandialabs/interspec/releases
- Can open many data formats
- Automatic Peak Fitting
- Automatic Background Subtraction
- Library of Gamma Ray Nuclides

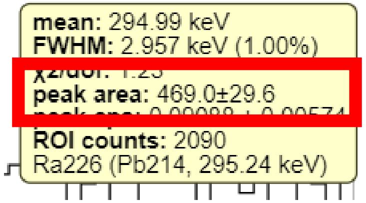


InterSpec Usage

- Open the Mine_Dust_Data.chn file
- View -> Chart Options -> Linear Y-Scale
- Zoom in by dragging right
- Zoom out by dragging left
- Double-click on a peak to fit it
  - Details show up in the bottom peak manager
- Right-click on a peak to refit

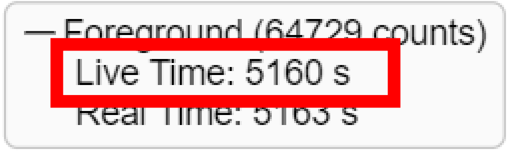
- Use Nuclide Search tab to identify peaks
  - Click on peak to automatically fill energy
  - Search for decays with high “Rel B.R.” = Relative Branching Ratio
  - InterSpec will sometimes list multiple “Parents” for the same decay. Just choose one.

InterSpec Parameters



N = "peak area" while hovering over peak fit

$$N = \Omega\, \epsilon\, \frac{Ig}{100}\, M\, t\, A$$



t = "Live Time" in box over spectrum

M = 884.4 g

tion | Nuclide Search

Parent	Energy (keV)	Diff.	Rel. B.R.	Profile	Decay	Parent H.L.
Ra228	911.20	0.66	0.40	0.56	Ac228→Th228	5.75 y
Th232	911.20	0.66	0.63	0.54	Ac228→Th228	1.4e+10 y
Ac228	911.20	0.66	1.00	0.51	Ac228→Th228	6.15 h
U236	911.20	0.66	0.00	0.46	Ac228→Th228	2.3e+07 y

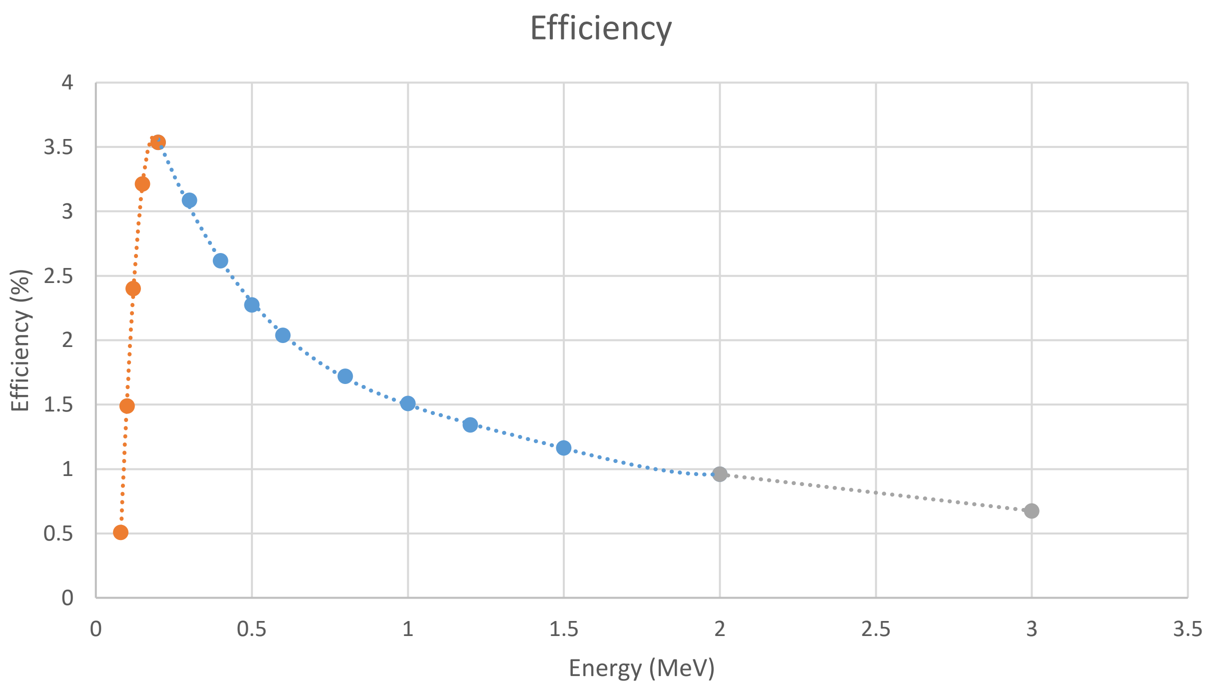
887.33 *10*	0.027 *3*	b⁻
901.26 *13*	0.016 *3*	b⁻
904.19 *3*	0.77 *3*	b⁻
911.204 *4*	25.8 *4*	b⁻
919.01 *13*	0.027 *3*	b⁻
921.98 *10*	0.0147 *21*	b⁻

BR = Use the Decay and Energy to look up the Branching Ratio on the Lund Site

Simulation Parameters

- The product $\Omega\,\epsilon$ is calculated by simulation.
- Open Mine_Dust_Efficiency.csv in Excel, Python, or Google Sheets
- Interpolate between given points

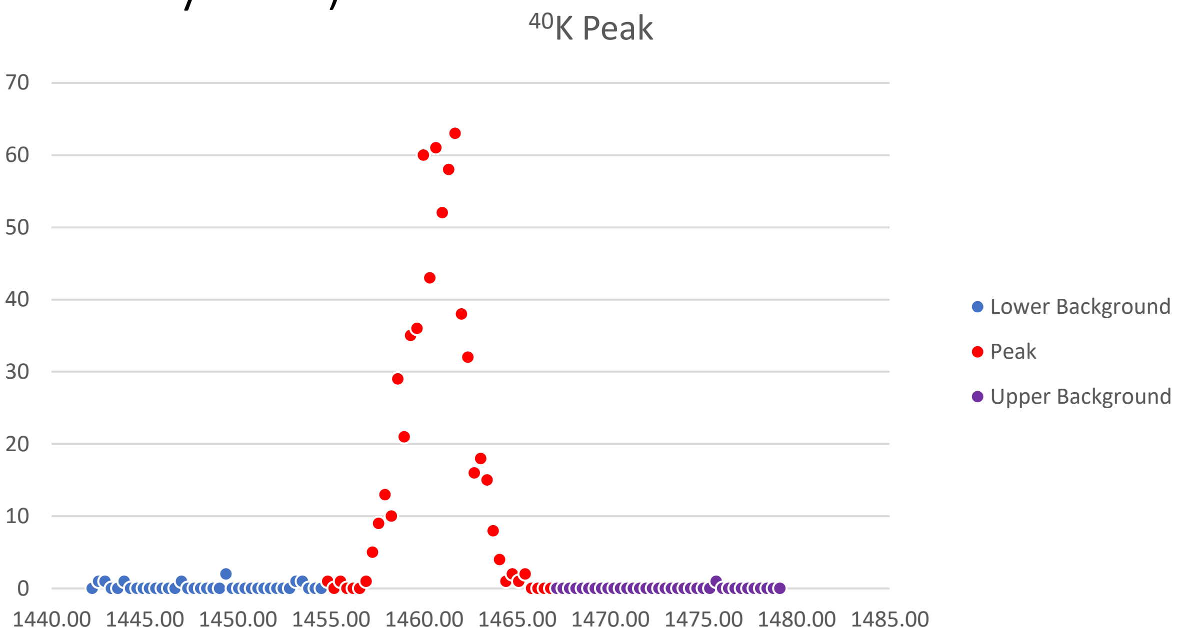
$$N = \Omega\,\epsilon\,\frac{Ig}{100}\,M\,t\,A$$



For example,
$\Omega\,\epsilon$ = .012 +/- 0.001
at 1750 keV

Integration Method

(Excel or Python)



- Integrate 2 to 3 peak widths around the peak
- Subtract off average background
- If same number of bins, $N_K = N_{Peak} - N_{LB}/2 - N_{UB}/2$
- For PGT detector (in keV)
  - $Width = 0.994 + 1.4e\text{-}2\sqrt{E} + 3.18e\text{-}4\,E$

Error Propagation

$$F = f(a, b)$$

$$\sigma_F{}^2 = \left(\frac{\partial F}{\partial a}\sigma_a\right)^2 + \left(\frac{\partial F}{\partial b}\sigma_b\right)^2$$

For linear multiplicative uncertainties:

$$F = \frac{ab}{c}$$

$$\sigma_F{}^2 = F^2\left(\frac{\sigma_a{}^2}{a^2} + \frac{\sigma_b{}^2}{b^2} + \frac{\sigma_c{}^2}{c^2}\right)$$

Error Comparisons

Measurement precision is given by $\frac{\sigma_F}{F}$

$$\frac{{\sigma_F}^2}{F^2} = \left(\frac{\partial F}{\partial a}\frac{\sigma_a}{F}\right)^2 + \left(\frac{\partial F}{\partial b}\frac{\sigma_b}{F}\right)^2$$

Source	Uncertainty (%)
Uncertainty on Counts	10.2
Detection Efficiency	5
Branching Ratio	1
Sample Mass	0.1
Livetime	.001
Total	11.4

- Usually summarized in an Error Table
- Since they are added in quadrature, only the largest ones matter.
- e.g. "Uncertainty on Counts" contributes 80% of the total

Rules of Thumb

- Dominant Uncertainties
  - > 1/3 of max uncertainty
  - These must be addressed to improve the measurement
  - Papers and reports must describe how these were estimated
- Secondary Uncertainties
  - 1/3 to 1/10 of max uncertainty
  - These could become dominant in an improved measurement
  - Reports should describe the general method used to estimate them (repeated measurements, simulations, etc.)
- Negligible Uncertainties
  - < 1/10 of max uncertainty
  - They must go in the error table
  - Reports should spend less than 1 sentence describing them.